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TECHNICAL MEMORANDUM

SRL-0002-TM

THE CALCULATION OF GROUND WAVE ATTENUATION IN THE HF BAND USING PROGRAM WAGNER

R.M. THOMAS and A.O. ZOLLO

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DECEMBER 1987

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R.M. Thomas and A.O. Zollo

S U M M A R Y

We present computational test results from a double precision version of the FORTRAN program 'WAGNER'. The potential value of this integral equation technique is its purported ability to model propagation losses over two-dimensional paths through irregular and inhomogeneous terrain. However the numerical integration algorithm can be affected by poor convergence and inaccuracy, particularly at frequencies above the MF band. We have investigated these properties in terms of selected key parameters and have derived empirical criteria governing convergence and physical accuracy. We find that calculations of basic transmission loss using WAGNER are subject to significant limitations at HF frequencies as the terrain becomes irregular and as the conductivity and dielectric constant of the ground both become smaller. On the other hand, the shadow loss due to an obstacle may be reliably calculated by WAGNER on the assumption that shadow loss is independent of ground electrical constants, thus permitting the use of dummy values of conductivity and dielectric constant to ensure that the physical accuracy criterion is satisfied.

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1. INTRODUCTION

Ott(ref.1,2) has formulated an integral equation technique for the calculation of ground wave propagation losses over paths characterised by irregular terrain and varying electrical ground constants (conductivity and dielectric constant). The calculation is performed by step-wise numerical integration along the transmission path of the sum of a direct ray and a ground-reflected ray, and is coded in the FORTRAN program 'WAGNER'.

References 1 and 2 presented example calculations at frequencies between 1 and 10 MHz showing results which are consistent with those obtained using alternative methods. Generally favourable comparisons with selected experimental measurements were also presented in references 3 and 4, indicating the reliability of the technique. The technique is however subject to certain qualifications, for example:

(a) the technique is spatially two-dimensional and treats only propagation along the great circle path between two antennas, neglecting side- and back-scattered radiation;

(b) care must be taken to ensure that the integration step length is sufficiently small to enable the solution to converge; however too small a step length will lead to excessively large program execution times;

(c) a frequency-coupled limitation exists on the maximum gradient of path terrain which may be treated accurately; this "heuristic uncertainty principle"(ref.1) is given as

$$|y'| \; f \lesssim 10$$

where y' is the gradient and f is the frequency in MHz, and shows that a gradient of 0.25 should return accurate loss calculations throughout the HF band up to a maximum frequency of 40 MHz;

(d) accuracy can be machine dependent, with small wordlength machines increasing the susceptibility to round-off errors unless double-precision floating point arithmetic is used.

(e) computations are subject to poorly understood numerical instability under certain conditions.

However, the potential advantages of the technique appear to outweigh the disadvantages. Within the constraints of the "heuristic uncertainty principle" it should be possible to treat a path having an arbitrary terrain profile and include variations in ground electrical constants, for example across a coastline. Reliability in such a calculation could permit a significant reduction in the need to perform propagation experiments in the field, with consequent savings of time, expense and manpower. While the residue series expansion method(ref.5,6) provides a reliable and quick means of calculating losses over smooth, homogeneous terrain it is unable to accommodate terrain irregularities, in contrast to WAGNER.

Alternative techniques for the estimation of losses due to terrain irregularities are based on knife-edge diffraction. Bullington(ref.7) presents a chart from which it is possible graphically to estimate the attenuation caused by a single knife-edge located between two antennas in free space. Its adaptation to the case of a single knife-edge on the surface of a smooth spherical Earth has resulted in a chart which gives the shadow loss of the obstacle with respect to smooth, spherical homogeneous Earth ground wave propagation, and has been verified experimentally(ref.8). Multiple knife-edges are not accommodated, however, and must be treated by other techniques, such as WAGNER.

We point out that while a hill may be conveniently modelled either by a Gaussian profile or by a knife-edge for the purpose of calculating wave attenuation, results differing by several decibels are likely to be obtained from the two methods, particularly in close proximity to the hill. However, the results of Ott(ref.1) indicate that such discrepancies diminish with distance and become unimportant at distances exceeding on the order of 5 times the 1/e full width of the hill. We therefore believe that with this qualification, comparisons between Gaussian and knife-edge profiles may be made.

1.1 The program

The mathematical details concerning the integral equation for ground wave propagation over irregular and inhomogeneous terrain have been described by Ott(ref.1,2) and will not be repeated here. The solution to the resulting linear Volterra integral equation is solved by the method of Wagner(ref.9), whence the title of the computer program. This solution involves subdivision of the transmission path into steps of the order of a wavelength in size and a summation in signal strength over all subintervals along the path. The techniques involved in obtaining the numerical solution are non-trivial and at this time a formal error analysis of the procedure apparently has not been made. It is certainly beyond the scope of this report. Consequently the user of WAGNER faces a lack of information on such matters as the convergence properties of the technique and the accuracy with which it models transmission losses, particularly within the HF band.

Our version of WAGNER was originally coded in single-precision but has been converted to double-precision to reduce round-off errors. Named W5D, it is compiled under VAX FORTRAN version 4.5 and runs on the HF Radar Division VAX 8200 under the operating system VMS version 4.4. We have tested the program for the case presented in figure 1 of reference 1, that is, a frequency of 1 MHz, ground conductivity of 0.01 S m^{-1}, dielectric constant of 10, an otherwise flat path of length 15 km containing a Gaussian hill of height 1 km located at a distance of 5 km from the transmit antenna. The integration subinterval or step size used in reference 1 is not specified but our work employed a step size of 100 m. The antennas are vertically polarised and located at ground level. The resulting basic transmission loss is graphed as a function of distance along the path in figure 1(a). Agreement with reference 1 is excellent, validating our version of the program at this frequency in the MF band. Note that the data in reference 1 are presented in terms of the amplitude attenuation function (f) with respect to twice the free space field which is related to the amplitude basic transmission loss L_b at wavelength λ, between isotropic antennas separated by a distance x, according to

$$L_b = 2f \cdot \frac{\lambda}{4\pi x}.$$

Our calculations are presented in terms of basic transmission loss in decibels (dB). Losses are represented by negative numbers. The execution time required to produce the results of figure 1(a) was 250 s. In general, execution time varies as the square of the number of integration steps. We point out that at 15 km the shadow loss resulting from the hill is about -10 dB with respect to smooth, spherical Earth propagation, in excellent agreement with the graphical estimate from reference 8. However if we move out of the MF band into the HF band we encounter problems. Figure 1(b) shows results for a frequency of 10 MHz, all other parameters remaining unchanged. It indicates that the shadow loss of -10 dB at 1 MHz has at 10 MHz been transformed into a gain of +41 dB. Since in this case the knife-edge technique graphically predicts a shadow loss of -18 dB, it is clear from the discrepancy of 59 dB that WAGNER has broken down.

2. TEST TECHNIQUES

Our initial attempts at applying WAGNER to real terrain at HF frequencies produced results such as figure 1(b) which were obviously in error. In view of the difficulties involved with a formal error analysis it was decided to carry out an "experimental" study of the intervals in certain key parameters for which the results of WAGNER could be relied upon. The aim was to develop empirical or heuristic "rules of thumb" which could be applied to predict whether a proposed calculation would be successful or not.

The key parameters selected for this study were integration step size, frequency, path length, terrain slope, ground conductivity and dielectric constant. The question of the reliability of any calculated result has two aspects. Firstly it is necessary to know whether the calculation has arrived at the convergence limit in the mathematical sense. Since the program does not iterate on the integration step size by testing the difference between successive loss calculations, it is not possible to know "a priori" how far any given result deviates from its convergence limit. Secondly, successful mathematical convergence of an algorithm does not necessarily produce a correct answer from the physical viewpoint. It is therefore necessary to compare each convergent solution with the loss estimated using an independent method for example the residue series expansion algorithm, in the case of a smooth Earth, or the graphical knife-edge method in the case of a single terrain obstacle. Thus we aim to produce two criteria, one describing the conditions necessary for convergence and the other similarly specifying physical accuracy.

Both convergence and accuracy were mapped at regular grid points in the space of the integral equation's key parameters. Calculations of basic transmission loss were carried out with uniformly spaced integration steps ranging down in size from 1000 to 10 m, at frequencies between 1 and 30 MHz, path lengths from 10 to 100 km, terrain gradients from 0 to 3, ground conductivities from 0.001 to 0.1 S m^{-1} and dielectric constants from 1.1 to 100.

Two types of terrain were employed, a smooth spherical homogeneous Earth of effective radius factor equal to 4/3 and a single Gaussian hill based on the terrain of figure 1 but permitting variable hill heights and ground electrical constants. Note that the maximum gradient of terrain is given in this case by approximately 10^{-3} times the hill height in metres.

3. RESULTS

3.1 Convergence

3.1.1 Effect of path length and frequency

Basic transmission losses were calculated over a smooth spherical Earth at path lengths L = 10, 20, 50 and 100 km using integration step sizes Δx ranging from 1000 m down to 10 m. A ground conductivity $\sigma = 0.003$ S m^{-1} and dielectric constant K = 3 were used at each of the frequencies f = 2, 10, 20 and 30 MHz. The results for L = 20 km are given in figure 2 in comparison with the residue series expansion result. It is evident that at 2 MHz a step size in excess of 1 km is adequate for convergence, while at 30 MHz the required step size has shrunk dramatically to only 10 m.

These results are more conveniently shown in figure 3 which represents two orthogonal planes through the 3-dimensional space of step size, frequency and path length, showing the boundary of the volume within which the basic transmission loss has converged to within 1 dB. Figure 3(a) indicates an approximately inverse relationship between path length and step size for a given frequency, while figure 3(b) indicates an approximately inverse square relationship between frequency and step size. We can therefore state an empirical convergence criterion in the form

$$\Delta x \lesssim \frac{k\lambda^2}{L} \qquad (1)$$

where λ is the wavelength in metres, Δx is in metres and L is in km, and the constant k is yet to be found.

3.1.2 Effect of terrain gradient

Real terrains exhibit slopes which vary from approximately zero for flat ground to very large values for almost sheer cliff faces. Large gradients would not normally be associated with Gaussian hills since mechanical stability considerations are likely to ensure that over geological time-scales the slopes of hills would settle towards equilibrium values of fairly modest size, say 0.5 or less. In spite of this, we have found it convenient to examine the influence of terrain gradient over a large range of values by making use of idealised Gaussian hill geometries and assuming that similar slopes will have similar effects on the performance of WAGNER, regardless of the type of topography involved. This approach follows the lead of Ott(ref.2).

The geometry employed for this study was based on that used for figure 1 but with the Gaussian hill height varied up to a maximum of 3000 m, corresponding to a maximum gradient $|y'| \sim 3$. Figure 4 relates values $|y'|$, and λ which just produce convergence with a step size $\Delta x = 100$ m. A quadratic curve which conveniently fits the data points is described by

$$\lambda = 18\,(8|y'|^2 - 2|y'| + 1) \qquad (2)$$

3.1.3 Effect of ground electrical constants

It was found that the parameters ground conductivity σ and dielectric constant K have a negligible effect on convergence.

3.1.4 Convergence criterion

We may use equation (1) to write the condition for convergence as

$$\lambda \gtrsim \sqrt{\frac{L\Delta x}{k}}\, f(|y'|)\, g(\sigma,k),$$

where the function g is identically unity (Section 3.1.3) and the function f equals unity for a slope of zero. For non-zero slopes, comparison with equation (2) shows that k = 4.6 and $f = 8|y'|^2-2|y'|+1$. If we conservatively adjust k downward to k = 2, providing a safety margin of about a factor of 2, we arrive at our convergence criterion given by

$$\Delta x \lesssim 2\lambda^2 L^{-1}(8|y'|^2 - 2|y'| + 1)^{-1} \qquad (3)$$

where Δx = required integration step size in metres

λ = wavelength ($10 \leq \lambda \leq 300$ m)

L = path length ($0 \leq L \leq 100$ km)

$|y'|$ = maximum value of terrain slope along the path ($0 \leq |y'| \leq 3$)

Being an empirical result, equation (3) holds only approximately within the tested parameter volume and cannot be guaranteed to hold elsewhere.

3.2 Accuracy

The existence of mathematical convergence is no assurance of physical accuracy. Therefore we varied parameters within the constraints of equation (3) in order to investigate how closely the convergent results of WAGNER agreed with basic transmission losses calculated by alternative methods, namely the residue series expansion for smooth Earth propagation, and the graphical knife-edge technique for single-hill terrains.

3.2.1 Effect of path length

It was found that for smooth spherical Earth propagation, WAGNER always converged to within 0.1 dB of the value of basic transmission loss predicted by the residue series expansion. This result appeared to hold everywhere within the same volume of parameter space as was used for the convergence study. In particular, path length variations appeared not to affect the accuracy of the final result, provided convergence had been achieved.

3.2.2 Effect of terrain gradient and frequency

Figure 5 shows how the accuracy of WAGNER varies with frequency in the case of a 500 m high hill located 5 km from the Tx antenna along a total path of 15 km, with $\sigma = 0.01$ S m^{-1} and K = 10. The convergent values of basic transmission loss are plotted and compared with the loss for smooth spherical Earth terrain and with the addition of the shadow loss predicted by the knife-edge graphical technique. It is evident that there is agreement up to a maximum frequency of only about 2 MHz and that above 5 MHz WAGNER incorrectly predicts a shadow gain with respect to smooth spherical Earth propagation, rather than a shadow loss.

This result and those of similar calculations for hills up to 3000 m in height, corresponding to terrain slopes $|y'|$ up to about 3.0, indicate that accuracy is governed by a condition of the approximate form

$$|y'|\ f \lesssim 1 \qquad (4)$$

where f is the frequency in MHz. This contrasts strongly with the "heuristic uncertainty principle" proposed by Ott (see section 1 above). Whereas Ott's result for $|y'| = 0.25$ predicts accuracy up to a maximum limiting frequency of 40 MHz, our equation (4) limits this maximum usable frequency to only 4 MHz.

3.2.3 Effect of ground electrical constants

Figures 6 and 7 present the results of a study of the effect of ground conductivity σ and dielectric constant K on the accuracy of the integral equation solution. Figure 6 is drawn in terms of shadow loss (or gain) versus frequency for different choices of the ground constants and for a terrain slope of 0.25. It shows that WAGNER agrees best with the knife-edge prediction over the 1 to 30 MHz frequency interval when the ground constant values are highest. In particular, for the low values of ground constants applicable to the Alice Springs region ($\sigma = 0.003$ S m^{-1}, K = 3), a terrain slope of 0.25 can be accurately modelled up to a maximum frequency of only 2 MHz. Calculations for additional terrain slopes resulted in figure 7, showing the maximum frequency which can be accurately used as a function of the ground constants.

In general, σ and K vary roughly in proportion to each other according to ground conditions and we find it convenient to treat the product σK as a single key parameter. Plotting its square root as in figure 7 permits the data to be represented on a more compressed horizontal scale. The results of figure 7 indicate that the maximum frequency which can be used in order to obtain accurate results is inversely proportional to the terrain slope (in agreement with equation (4)) and approximately proportional to the fourth root of the product σK.

3.2.4 Accuracy criterion

The above results lead to an empirical accuracy criterion given by

$$|y'|\ f\ (\sigma K)^{-\frac{1}{4}} \lesssim 1.8 \qquad (5)$$

In the Alice Springs region we may have typically $|y'| \sim 0.25$, $\sigma \sim 0.003$ S m^{-1} and $K \sim 3$, implying that accurate basic transmission loss results can be obtained up to a maximum frequency of only about 2 MHz. In this case therefore, WAGNER cannot be used to calculate basic transmission losses at frequencies in the HF band.

Alternatively, equation (5) shows that at a frequency of 10 MHz in the Alice Springs region, accuracy can be assured only for terrain slopes less than about 0.06 or an elevation change of 60 m over a distance of 1 km. Thus our version of WAGNER appears to be limited to low frequencies and gentle terrains, if basic transmission loss is to be calculated with acceptable accuracy.

3.3 "Pathological" behaviour

While the results described above are disappointing in terms of possible applications of WAGNER in the HF band, they nevertheless indicate a smooth and regular variation with respect to the key parameters. However occasional sharp departures from this predictable behaviour have been observed. For example, in the case of smooth spherical earth propagation at 10 MHz, with $\sigma = 0.003$ S m^{-1}, K = 3, L = 100 km, and $\Delta x = 100$ m, the calculated basic transmission loss appeared to be converging as expected. However further reduction of the step size to 50 m surprisingly produced a sharply divergent result for distances in excess of 50 km. Additional reduction in step size then led to a recovery with convergence finally being achieved for $\Delta x = 20$ m.

The user is warned of the possibility of occasional rare occurrences of this type. One safeguard is to always examine the trend of the basic transmission loss as a function of distance along a path, looking for irregular behaviour.

4. DISCUSSION

The results of Section 3 above show that even when a calculation by WAGNER of basic transmission loss has converged to a stable value, the result remains subject to a severe physical accuracy constraint which renders our version of WAGNER almost useless in the HF band. This is particularly so when the ground electrical constants have low values, as in the case of the arid desert environment surrounding Alice Springs.

However in many applications the total basic transmission loss may not be the required variable. It may suffice to calculate only the shadow loss (relative to smooth spherical Earth propagation) due to one or more terrain irregularities. Since shadow loss depends mainly on topography and very little on the electrical constants of the terrain, it may be possible to calculate shadow loss by using "dummy" values of conductivity and dielectric constant which are chosen to be high enough to ensure numerical accuracy (equation (5)). The program could be run first for the terrain under consideration and then for a smooth spherical Earth, and the first result divided by the second in order to obtain the shadow loss. If shadow loss depends only on the frequency and on the geometrical dimensions of the obstacle, a reliable result should be obtained, with the dummy ground constants being self-cancelling. For the case of a single obstacle this result should agree well with the graphical estimate using reference 8. In the case of arbitrarily complex terrains WAGNER alone possesses the potential to produce believable shadow loss results, subject to the constraining equation (5).

We are able to demonstrate the usefulness of this approach. Figure 8 compares the shadow loss predicted by the knife-edge technique with two results from WAGNER, firstly a single Gaussian hill approximation to the terrain and secondly the actual terrain interpolated into intervals equal in size to the specified integration step size Δx. The WAGNER calculations were carried out for a dummy conductivity of 50 S m^{-1} and a dummy dielectric constant of 500. Also shown are actual shadow loss data measured over this path. The calculations using the actual terrain profile agree best with the observations at the lower frequencies but tend to overestimate the loss above 15 MHz. The Gaussian profile predicts a frequency variation of shadow loss which is not matched by the rather flat variation of the observations. The graphical knife-edge estimates also fall away with frequency rather more rapidly than is actually measured, but are nevertheless in fair agreement. Application of the technique to other paths has also been generally successful(ref.8).

The above results indicate that shadow loss in the HF band may be reliably obtained from WAGNER provided firstly that the convergence criterion is satisfied, and secondly that the accuracy criterion is satisfied by using high dummy values of ground conductivity and dielectric constant. That the method proves to be satisfactory relies on shadow loss being largely independent of ground electrical constants.

5. CONCLUSION

In the absence of any reported theoretical analysis, we have empirically derived heuristic criteria which govern the convergence behaviour and physical accuracy of Ott's integral equation approach to the calculation of ground wave propagation losses over irregular and inhomogeneous terrain. We have found that for irregular terrain the existence of mathematical convergence does not necessarily imply a physically accurate calculation.

The computer program WAGNER which implements the integral equation calculation has been tested for homogeneous ground by varying selected key parameters over intervals pertinent to ground wave propagation work being carried out in conjunction with HF radar studies. These parameters and their test intervals are as follows:

Integration step size (uniform)	Δx	:	10 to 1000 m
Frequency	f	:	1 to 30 MHz
Path length	L	:	10 to 100 km
Terrain maximum slope	$\lvert y' \rvert$	:	0 to 3.0
Product of ground conductivity and dielectric constant	(σK)	:	10^{-3} to 10^{4} S m^{-1}

The following heuristic criteria were found to govern the mathematical convergence and physical accuracy of the calculated basic transmission loss.

Mathematical convergence:

$$\Delta x < 2\lambda^2 L^{-1}(8|y'|^2 - 2|y'| + 1)^{-1}$$

Physical accuracy:

$$|y'|\ f\ (\sigma K)^{-\frac{1}{4}} < 1.8$$

It is stressed that the empirical origin of these expressions means that they are not unique and their validity cannot be guaranteed outside the tested parameter ranges specified above.

While our results confirm the usefulness of WAGNER in calculating basic transmission loss near a frequency of 1 MHz, they demonstrate serious accuracy difficulties at higher frequencies. In the case f = 10 MHz, $|y'|$ = 0.25, σ = 0.003 S m^{-1}, K = 3 and L = 20 km, mathematical convergence may be achieved provided the integration step size Δx is reduced to about 100 m. On the HF Radar Division VAX 8200 running under the operating system VMS version 4.4 and using VAX FORTRAN version 4.5, the execution time for this calculation is approximately three minutes. Convergence is therefore not a difficulty except possibly at the high extremes of terrain slope and path length when small step sizes and hence a large number of steps are required. Since execution time varies as the square of the number of integration steps such a calculation may run for many hours, but convergence will ultimately be reached. On the other hand, physical accuracy appears as a much more serious problem and basic transmission loss over the above path can be modelled by WAGNER to an accuracy of better than 3 dB only for frequencies below 2 MHz. The presence of hills of only modest size therefore effectively precludes the use of WAGNER for the calculation of basic transmission loss in the HF band. This result does not appear to have been spelt out by the authors of previous reports dealing with WAGNER.

If it is desired only to determine the relative shadow loss at HF due to irregular terrain along the path, it is feasible to perform the integral equation calculation using unrealistically high ground electrical constants in order to guarantee physical accuracy and then compare the result with the smooth spherical Earth calculation carried out with the same parameters. The dummy electrical constants effectively cancel themselves out in the process and therefore do not affect the derivation of the shadow loss. The demonstrated viability of this technique permits WAGNER to be used at HF for arbitrary multiple hills, which are not easily treated by the graphical knife-edge technique.

Importantly, our condition on physical accuracy is in disagreement with the condition given by Ott(ref.1). Whereas Ott's condition implies that terrain slopes of the order of 1 in 4 can be treated throughout the HF band up to a maximum frequency of 40 MHz, we find that our upper frequency limit is actually 4 MHz, assuming $\sigma = 0.01$ S m^{-1} and $K = 10$; the HF band is therefore effectively excluded from calculations of basic transmission loss unless larger values of σ and K can be employed.

Finally, we emphasize that the results presented in this report were obtained using our double-precision version of WAGNER, locally known as W5D. It is possible that more robust versions of WAGNER have evolved elsewhere. Every effort has been made to acquire versions currently in use in other parts of the world but without success. However this effort is continuing. The authors will be happy to supply a copy of W5D upon request.

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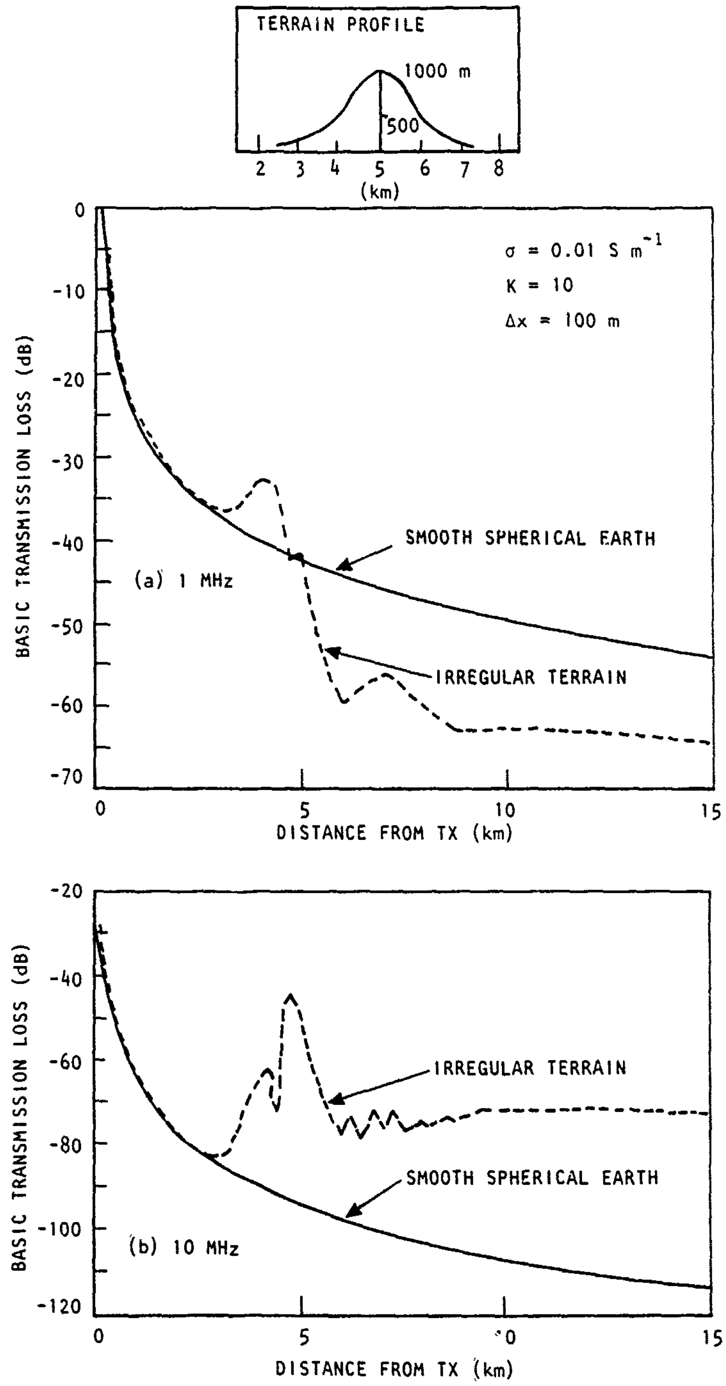

Figure 1. Calculation of basic transmission loss for the path given by Ott (figure 1, reference 1)

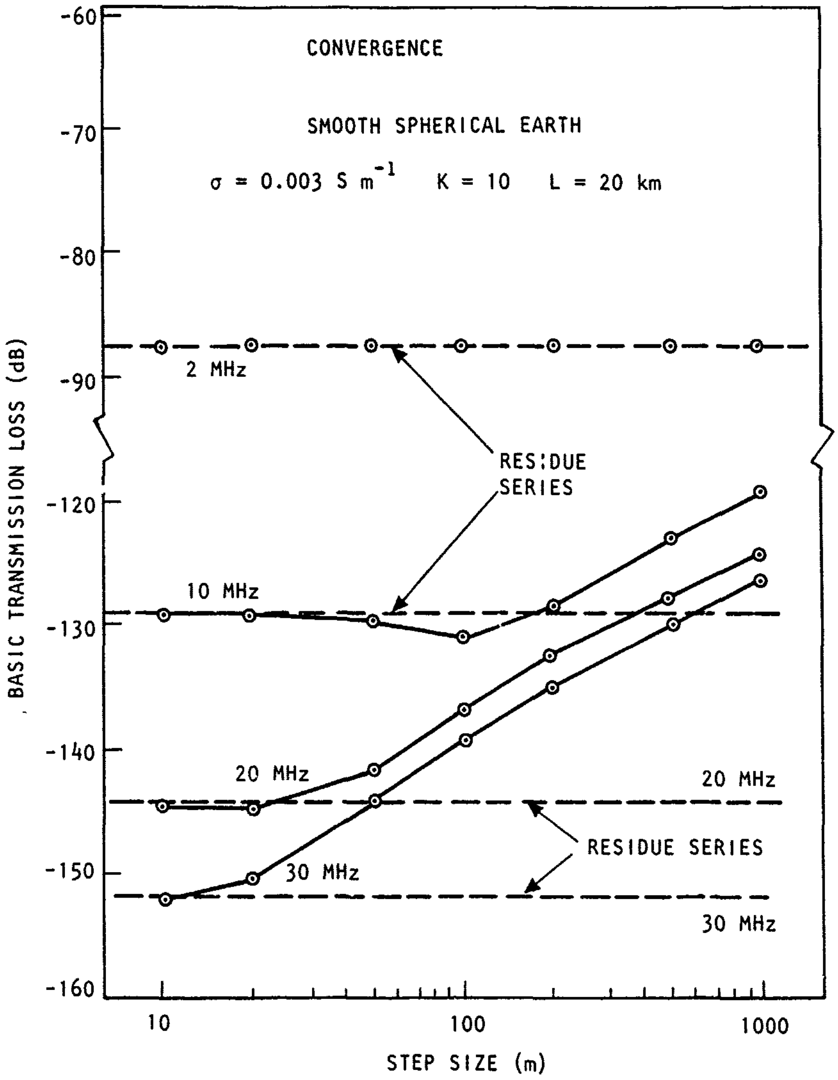

Figure 2. Convergence behaviour for 20 km path over smooth spherical Earth

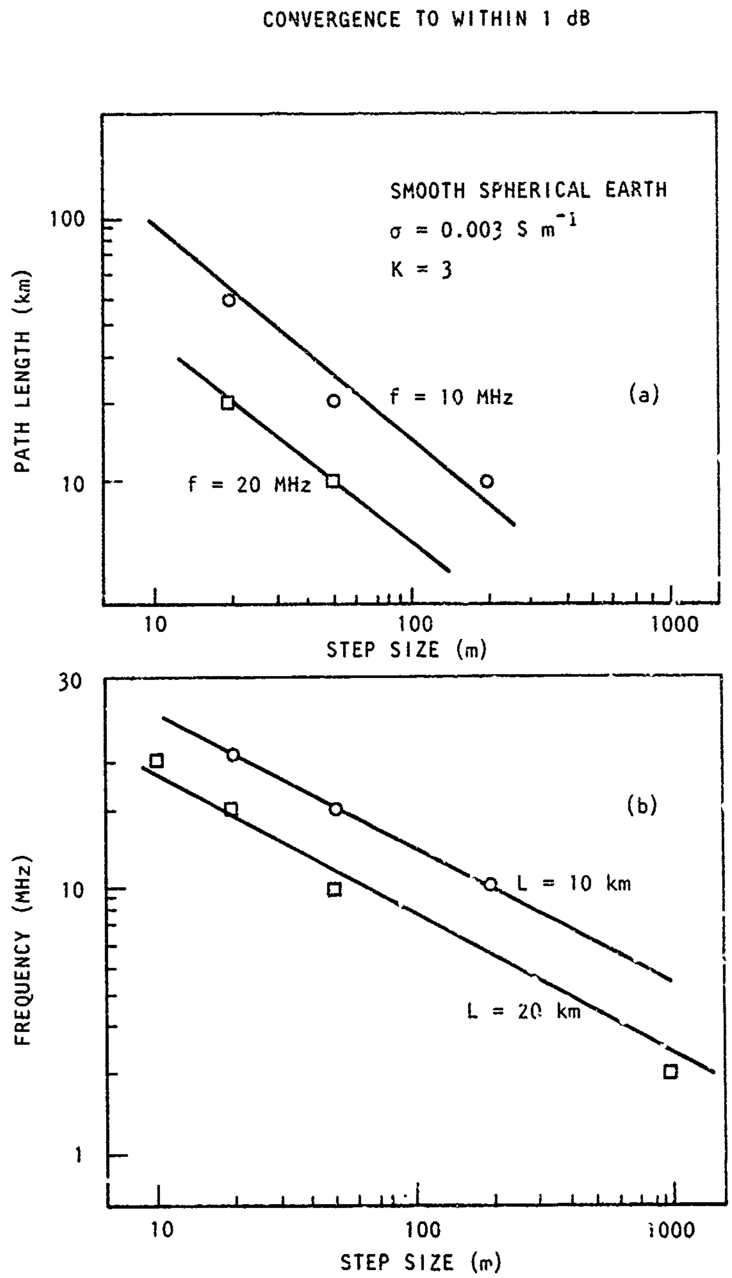

Figure 3. (a) Maximum path lengths and step sizes for convergence at a given frequency (b) Maximum frequencies and step sizes for convergence over a path length

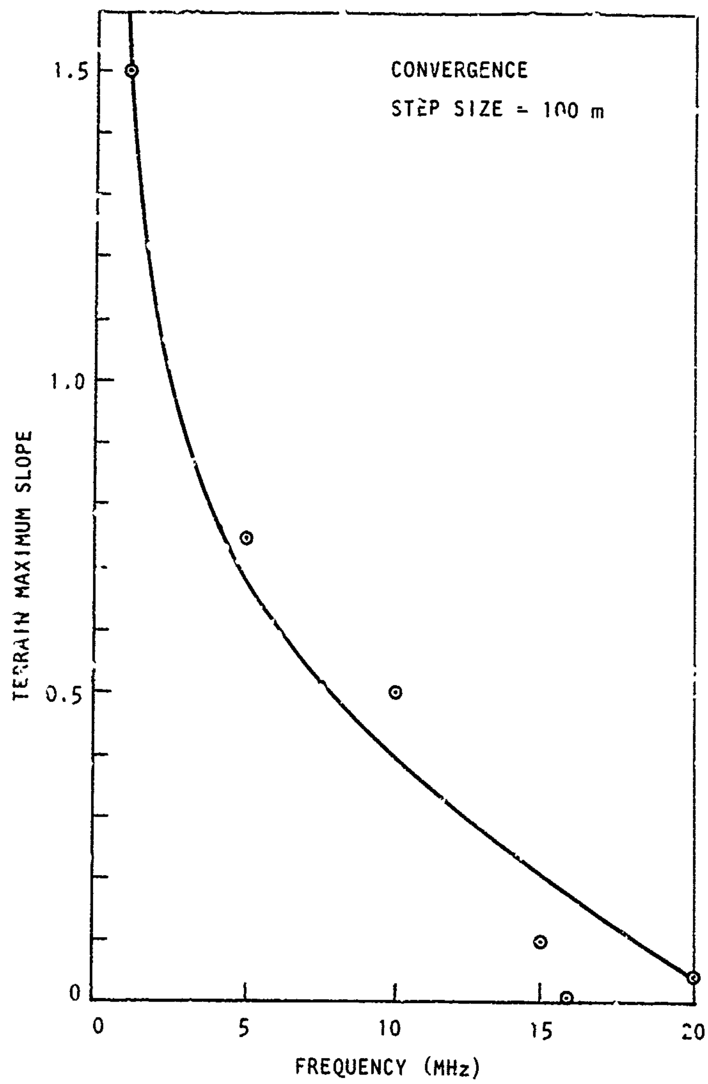

Figure 4. Relationship between maximum terrain slope and maximum frequency for convergence at a step size of 100 m

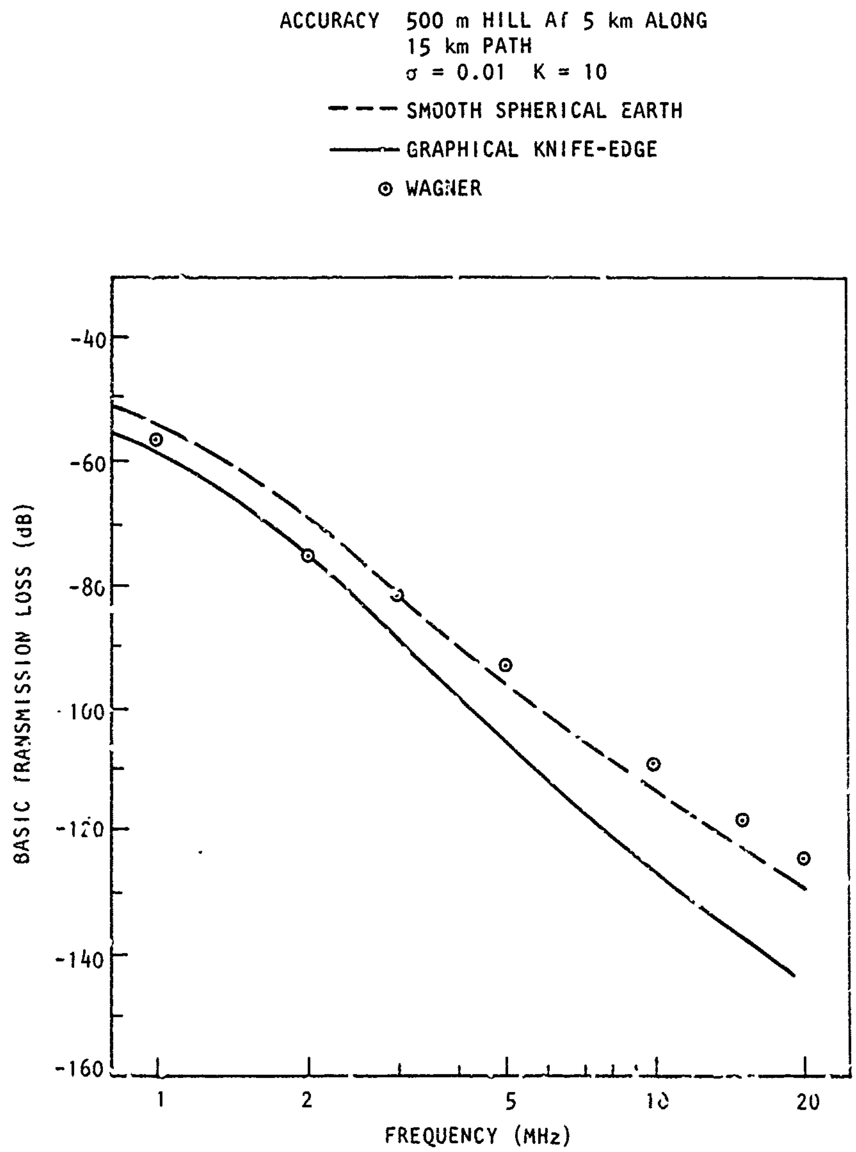

Figure 5. Accuracy of WAGNER for path with 500 m high hill, compared with knife-edge estimated loss

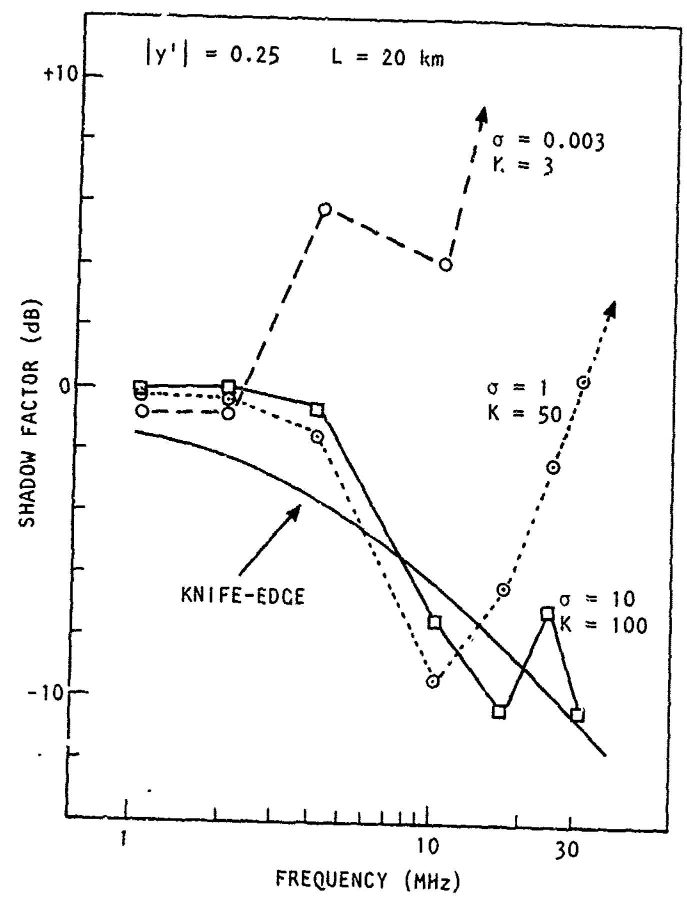

Figure 6. Dependence of accuracy on ground electrical constants

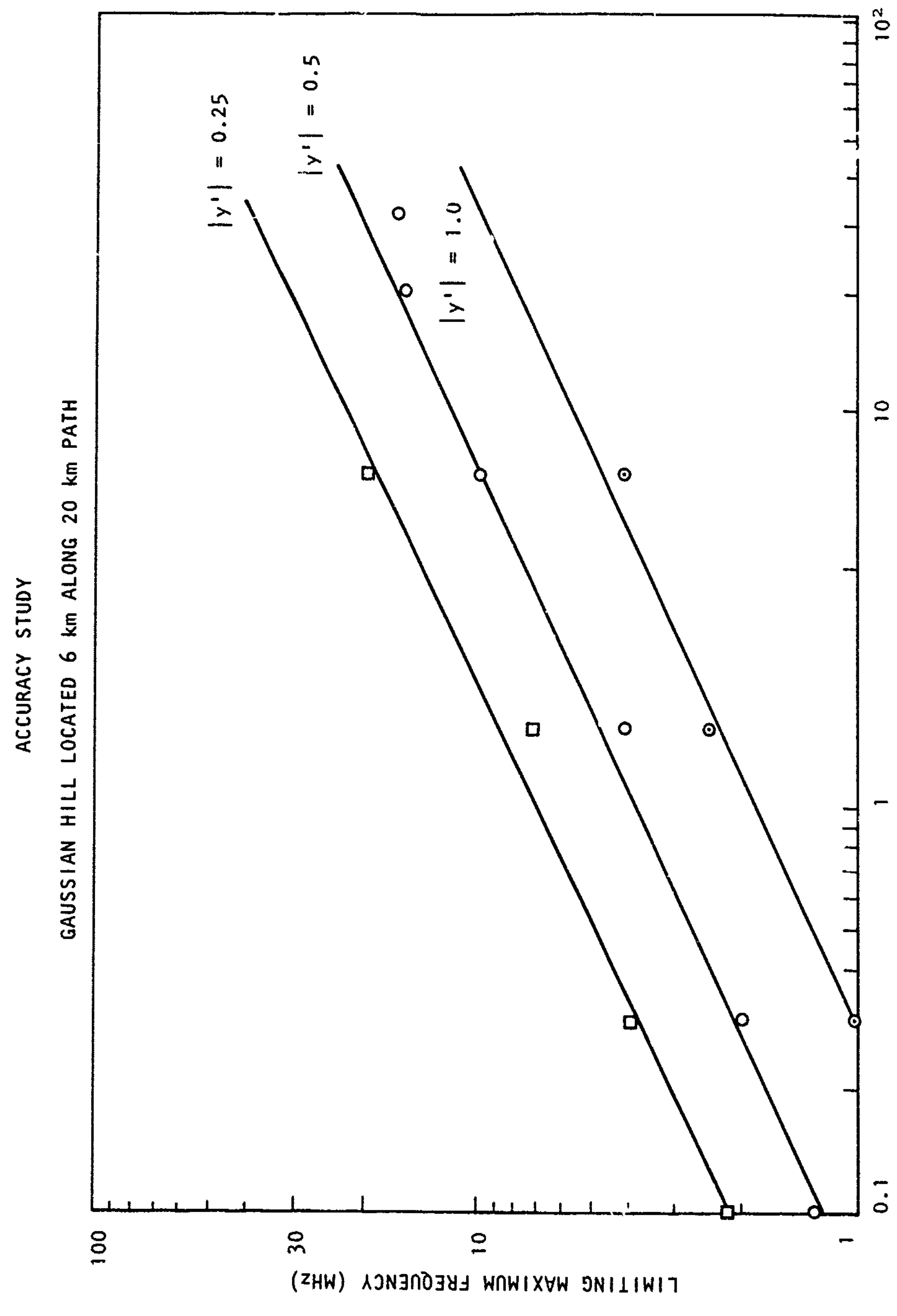

Figure 7. Maximum frequency for accuracy in terms of ground electrical constants and terrain slope

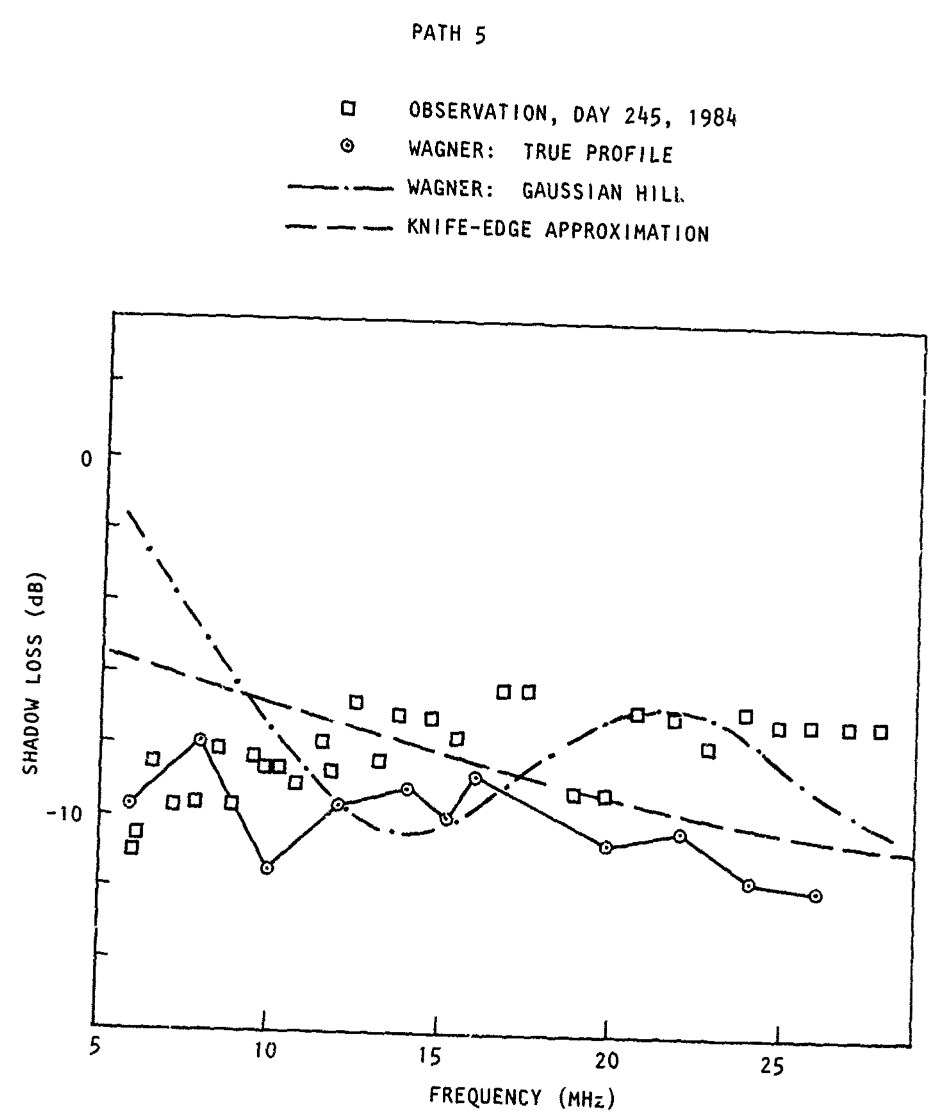

Figure 8. Comparison with observation of different calculations of shadow loss

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AD-A 200 049

Security classification of this page: UNCLASSIFIED

1 DOCUMENT NUMBERS

AR Number: AR-005-341

Series Number: SRL-0002-TM

Other Numbers:

2 SECURITY CLASSIFICATION

a. Complete Document: Unclassified

b. Title in Isolation: Unclassified

c. Summary in Isolation: Unclassified

3 DOWNGRADING / DELIMITING INSTRUCTIONS

4 TITLE

THE CALCULATION OF GROUND WAVE ATTENUATION IN THE HF BAND USING PROGRAM WAGNER

5 PERSONAL AUTHOR (S)

R.M. Thomas and
A.O. Zollo

6 DOCUMENT DATE

December 1987

7 7.1 TOTAL NUMBER OF PAGES 18

7.2 NUMBER OF REFERENCES 10

8 8.1 CORPORATE AUTHOR (S)

Surveillance Research Laboratory

8.2 DOCUMENT SERIES and NUMBER
Technical Memorandum
0002

9 REFERENCE NUMBERS

a. Task: DEF 87/200

b. Sponsoring Agency: PDC Division
Department of Defence

10 COST CODE

777991-141

11 IMPRINT (Publishing organisation)

Defence Science and Technology
Organisation Salisbury

12 COMPUTER PROGRAM (S)
(Title (s) and language (s))

13 RELEASE LIMITATIONS (of the document)

Approved for Public Release

Security classification of this page: UNCLASSIFIED

Security classification of this page : UNCLASSIFIED

14	ANNOUNCEMENT LIMITATIONS (of the information on these pages)
	No limitations

15 DESCRIPTORS		16 COSATI CODES
a. EJC Thesaurus Terms	Computer programs, Ground wave propagation, Attenuation, Transmission loss,	0046H
b Non - Thesaurus Terms	Wagner (computer program), Australia. (mgm/RH)	

17 SUMMARY OR ABSTRACT
(if this is security classified, the announcement of this report will be similarly classified)

We present computational test results from a double precision version of the FORTRAN program 'WAGNER'. The potential value of this integral equation technique is its purported ability to model propagation losses over two-dimensional paths through irregular and inhomogeneous terrain. However the numerical integration algorithm can be affected by poor convergence and inaccuracy, particularly at frequencies above the MF band. We have investigated these properties in terms of selected key parameters and have derived empirical criteria governing convergence and physical accuracy. We find that calculations of basic transmission loss using WAGNER are subject to significant limitations at HF frequencies as the terrain becomes irregular and as the conductivity and dielectric constant of the ground both become smaller. On the other hand, the shadow loss due to an obstacle may be reliably calculated by WAGNER on the assumption that shadow loss is independent of ground electrical constants, thus permitting the use of dummy values of conductivity and dielectric constant to ensure that the physical accuracy criterion is satisfied.

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